

ACKNOWLEDGEMENTS

The author wishes to acknowledge the guidance provided by Dr. M.W. Smith, Department of Geography, Carleton University, in the preparation of this paper. Appreciation is also expressed to Dr. R.J.E. Brown, Division of Building Research, National Research Council of Canada, for supplying subsurface thermal data for the Yellowknife area, and Dr. A.S. Judge, Earth Physics Branch, Geological Survey of Canada, for supplying information regarding the thermal properties of bedrock at Yellowknife and the Eagle Plain . Finally, Dr. H.M. French, University of Ottawa, provided valuable guidance on several occasions during the preparation of this paper.

TABLE OF CONTENTS

	Page
Acknowledgements.....	i
Table of Contents.....	ii
List of Tables.....	iii
List of Figures.....	iv
 1.0 INTRODUCTION.....	 1
1.1 The Ground Thermal Regime.....	1
1.2 Surface Energy Balance and Computer Simulation Models.....	4
1.3 Methodology.....	5
1.4 The Computer Model.....	6
 2.0 TEST RESULTS: YELLOWKNIFE.....	 7
2.1 Study Area.....	7
2.2 Test Results.....	11
 3.0 SIMULATION: EAGLE PLAIN.....	 17
3.1 Study Area.....	17
3.2 Input Data.....	21
3.3 Test Results.....	23
3.4 Discussion.....	32
 4.0 CONCLUSION.....	 34
5.0 REFERENCES.....	37

LIST OF TABLES

Table		Page
1	Site specific surface, and subsurface thermal properties of the "Blackrock" site, Yellowknife.....	12
2	Climate data, Dawson Airport, and Old Crow.....	20
3	Site specific surface and subsurface thermal characteristics for the Eagle Plain.....	22
4	List of site conditions simulated using MICRO, and corresponding maximum active layer depths.....	24
5	Estimated Solar Radiation, and Atmospheric Transmissivity values for the Eagle Plain, 1976-1977.....	25

LIST OF FIGURES

Figure		Page
1	Flow diagram of the computer program MICRO.....	8
2	Test area, Yellowknife, Northwest Territories.....	9
3	A graphic representation of the predicted and observed thermal regimes for Yellowknife.....	13
4	A plot of the predicted and observed thermal envelopes for Yellowknife.....	14
5	Predicted and observed temperatures at 1.0, 5.0, and 10.0 metre depths.....	16
6	Location map of Eagle Plain, northern Yukon Territory.....	18
7	Predicted thermal regime for horizontal limestone and sandstone surfaces in the Eagle Plain.....	27
8	Predicted thermal envelopes for the Eagle Plain.....	28
9	Predicted thermal regimes for south facing limestone and sandstone bedrock slopes of 10 and 30 degrees, Eagle Plain.....	30
10	Predicted thermal regimes for north facing limestone and sandstone bedrock slopes of 10 and 30 degrees, Eagle Plain.....	31

1.0 Introduction

Permafrost refers to the thermal condition of earth materials when their temperature remains below 0°C for a period greater than one year (Brown and Kupsch, 1974). In Canada, permafrost can be expected north of the -1.0°C mean annual isotherm (Brown, 1978). Based on this assumption, approximately 50.0% of the land surface of Canada is underlain by permafrost (Brown, 1970, p. 1).

This paper investigates the ground thermal regimes of bedrock in two areas of permafrost. Using the numerical simulation model MICRO (Smith, 1977), the predicted bedrock temperatures in the Yellowknife area are calculated and compared with observed data. The same model is then used to predict the thermal regime of bedrock sites in the Eagle Plain area of the northern interior Yukon. Also included in the Eagle Plain analysis is an investigation of the predicted effects of slope and aspect on the thermal regime.

1.1 The Ground Thermal Regime

The range and distribution of temperature in the upper layers of the earth's surface constitute the ground thermal regime. In general, the ground thermal regime is a function of the surface heat balance expressed in terms of the surface temperature, the thermal properties of the earth materials and the geothermal gradient (Gold and Lachenbruch, 1973).

For example, the seasonal variation in surface temperature produces an annual subsurface temperature oscillation the amplitude of which decreases with depth. The depth at which the seasonal amplitude of oscillation is zero is termed the level of zero annual amplitude. As a

generalization, the range of temperature or maximum variation for any depth below the surface can be determined by solving the exponential function:

$$T_R = 2T_o \exp^{-x\sqrt{\pi/\alpha p}} \quad (1)$$

where T_R is the temperature range ($^{\circ}\text{C}$) at depth x (cm), T_o is the amplitude of temperature oscillation at the surface, p is the period (seconds), and α is thermal diffusivity (cm^2/sec) (Ingersoll, Zobel and Ingersoll, 1948). This simple model assumes many things (e.g. homogeneous substrate) and ignores such factors as the presence of water and the zero curtain phenomenon.

The lag which progressively develops with the downward penetration of a thermal wave can be calculated by:

$$T_x = \frac{x}{2} \sqrt{\frac{p}{\pi\alpha}} \quad (2)$$

where T_x is the lag time (seconds) at depth x (cm) (Ingersoll, Zobel and Ingersoll, 1948). From equation 2, the velocity of the thermal wave is derived by:

$$V = 2\sqrt{\frac{\pi\alpha}{p}} \quad (3)$$

where V is the velocity (cm/second) (Ingersoll, Zobel and Ingersoll, 1948). It follows that temperature fluctuations are greatest in the upper layers of the earth materials being considered. With respect to the effectiveness of freeze-thaw processes, this implies that such processes are most effective near the surface. Below the depth of zero annual amplitude, heat flow from within the earth (the geothermal gradient) results in an increase in ground temperature with depth.

Assuming conductive heat transfer, the important physical properties that determine the response of earth materials to a heat flux are the thermal conductivity and thermal diffusivity (Judge, 1973). The thermal conductivity of the ground governs the thermal response to a transient disturbance. Thermal diffusivity can be expressed in terms of thermal conductivity and volumetric heat capacity (equation 4):

$$\alpha = \frac{K}{C_v} \quad (4)$$

where α is the thermal diffusivity, K is thermal conductivity and C_v is volumetric heat capacity.

The volumetric heat capacity (C_v) is a function of the specific heat (c) and density (ρ):

$$C_v = \rho c \quad (5)$$

The presence of water, either at the surface or in the ground, significantly alters the ground thermal properties. Wet soils display higher thermal diffusivities and thermal conductivities than dry soils. The fact that the conductivity of ice is four times that of water further complicates the thermal regime in frozen ground. However, since rocks are considerably less porous, the effect of water or ice in the system will not be as significant. Rock tends to display considerably higher thermal conductivity than soil, consequently the thermal diffusivity is higher as well (Ingersoll, Zobel and Ingersoll, 1948; Judge, 1973). Bedrock systems tend to be more sensitive to changes in surface temperature and the effect of external variables (e.g. vegetation, snowcover, slope and aspect).

1.2 Surface Energy Balance and Computer Simulation Models

The earth's surface gains or loses heat energy by radiation, evaporation, convection into the air and conduction into the ground. The energy exchange associated with these processes must be in balance at all times:

$$RN + LE + H + S = 0 \quad (6)$$

where RN is net radiation, LE is the evaporation energy flux (latent heat), H is the convective energy flux (sensible heat) and S is conduction into the ground (ground heat flux), (Gold et al., 1972; Outcalt, 1972; Smith, 1977).

The temperature at the earth's surface is determined by this surface energy balance. Equilibrium temperature theory states that "for any specified set of astronomical-temporal, atmospheric, and surface boundary conditions, there is one, and only one surface temperature that will balance the energy conservation equation at the earth's surface" (Outcalt, 1972, p. 629). The equilibrium surface temperature (TEQ) can be calculated for any given weather and surface conditions by iteratively solving all the components of the surface energy balance in terms of surface temperature (Smith, 1977).

Several energy balance models have been developed (e.g. Myrup, 1969; Outcalt, 1972; Outcalt et al., 1975). In the past, predictive models of ground thermal regimes expressed surface boundary conditions in terms of surface temperature or heat flux (Lachenbruch, 1959; Nakano and Brown, 1972). More recently it has been shown that a more accurate boundary condition is expressed by the surface energy balance equation (Myrup, 1969; Outcalt, 1972; Smith, 1977).

The computer simulation model MICRO has been tested extensively for both the Canadian Arctic (Eureka) and southern Ontario (Guelph and Ottawa) with a considerable amount of success (Smith, 1975, 1977; Smith and Tvede, 1976). In this study, the computer model MICRO is used to predict the surface energy and ground thermal regimes for two areas in the Canadian North characterized by extensive bedrock exposure.

1.3 Methodology

This study is divided into two parts. The first part simulates the ground thermal regime of the Yellowknife area for a fifteen-month period from October 1969 to December 1970. Standard climatological data from the Atmospheric Environment Service, site-specific characteristics and subsurface thermal properties are used as inputs in the MICRO model. The predicted values are compared with observations made by the National Research Council of Canada (Brown, 1973). The second part of this study simulates surface energy and ground thermal regimes of the Eagle Plain, northern Yukon Territory. MICRO is used to predict the ground temperatures of limestone and sandstone bedrock on north and south-facing slopes of 10° and 30° . Since the nearest weather station is Dawson, and the only Yukon station recording incoming solar radiation is Whitehorse, it is assumed that the climate data for Dawson adequately represent the interior northern Yukon including the Eagle Plain. It is further assumed that atmospheric conditions limiting incoming direct short-wave radiation are uniform throughout the Yukon.

Numerical simulation models of Garnier and Ohmura (1968) and Fuggle (1970) enable the calculation of incoming short-wave radiation on slopes. Fuggle's model is used to calculate the effective atmospheric transmissivity values for Whitehorse from known solar radiation data.

These values are used along with other Eagle Plain data (e.g. declination, latitude, azimuth and gradient) to predict direct incoming short-wave radiation on flat surfaces, and also north and south-facing slopes of 10° and 30° . These results are then used as inputs into MICRO.

1.4 The Computer Model

The computer program MICRO described in Smith (1977) utilizes a two-stage approach. In the first stage, inputs of weather data (solar radiation, cloud cover, cloud type, air temperature, wind speed, relative humidity, atmospheric pressure and snowfall) together with certain site-specific surface characteristics (albedo, roughness, wetness) are used to solve the surface energy balance. Each of the components of the energy balance equation is expressed as a function of surface temperature, and iterative solution of this equation yields the equilibrium surface temperature (TEQ). The equilibrium surface temperature along with the energy balance components are the final result of the first stage of the program.

In the second stage, the surface temperature solution is used as the boundary condition, together with specific ground thermal properties to predict the ground thermal regime. This portion of the program uses the heat conduction equation to predict the ground temperature pattern. Also included in the model are considerations of the energetics of freezing and thawing and variability of soil layers. The solution is one-dimensional and ignores energy fluxes in a horizontal direction. A further simplification is the lack of consideration given to unfrozen pore water and moisture migration during freezing. The effect of unfrozen pore water could be incorporated if sufficient information were available.

The model thus predicts the ground thermal regime as a function of microclimate, site-specific surface conditions and subsurface thermal properties. This approach makes it possible to relate spatial and temporal variations of thermal regimes to site-specific characteristics. Figure 1 presents a diagram of the model flow design. A listing of the program, the required inputs, outputs and equilibrium surface temperature computations are presented in Smith (1977).

In tests conducted by Smith (1975; 1977) and Smith and Tvede (1976), the computer model demonstrated an acceptable level of accuracy in the prediction of ground thermal regimes for both permafrost and seasonally frozen soils. The latter study displays the model's value as a predictive tool in engineering and construction.

2.0 Test Results, Yellowknife, N.W.T.

In previous studies (Smith, 1975, 1977; Smith and Tvede, 1976), MICRO demonstrated an acceptable level of accuracy in the prediction of surface energy and subsurface thermal regimes. Results obtained by Lewkowicz (1978), however, were not as favourable. All previous tests were concerned with the simulation of thermal conditions of soils; thus far, the model is untested in consolidated bedrock.

Yellowknife, N.W.T. was selected as the test area for two reasons: (1) the availability of weather observations and (2) the availability of bedrock temperature observations to a depth of 15.0 metres measured by the National Research Council of Canada (Brown, 1973).

2.1 Study Area

Yellowknife is located approximately 180 metres above sea level on the north shore of Great Slave Lake (Figure 2). Climate data are

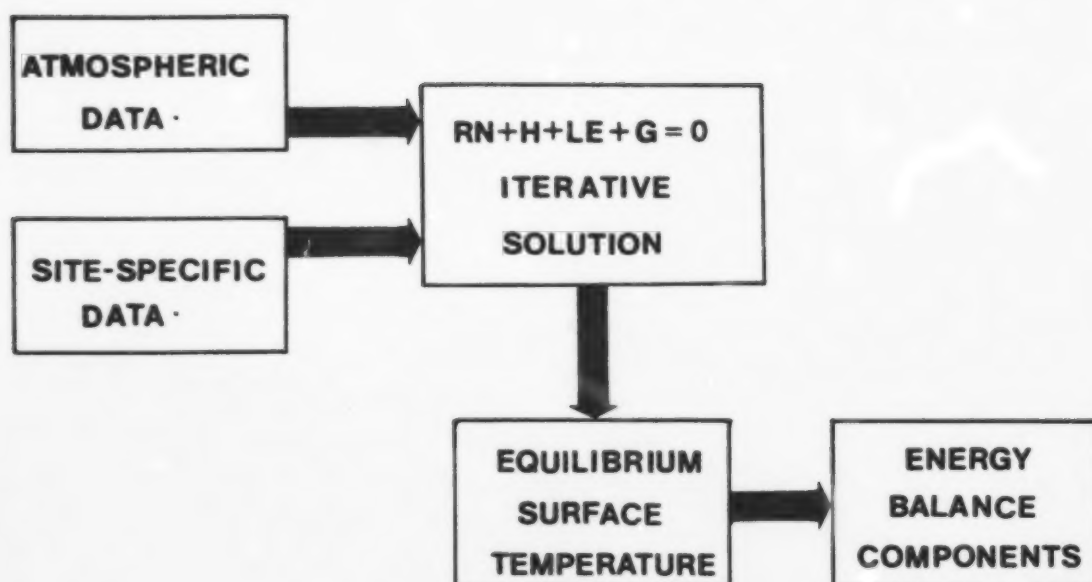
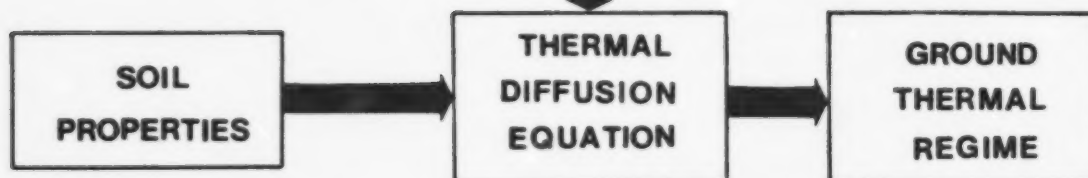
Stage 1:**Stage 2:**

FIGURE 1: Flow diagram of the computer program MICRO (Smith, 1977)

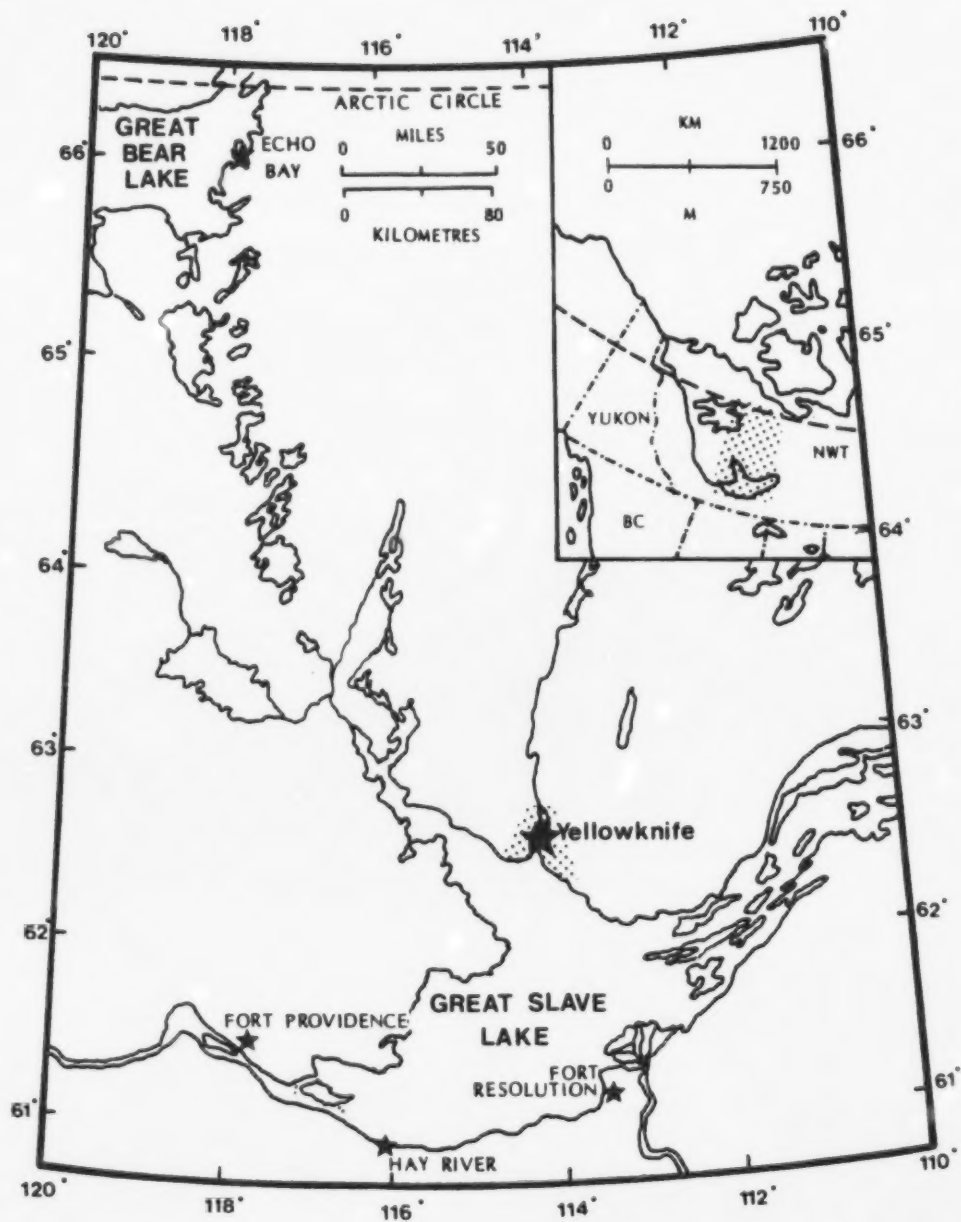


FIGURE 2: Test area, Yellowknife, Northwest Territories

available from both the Yellowknife Airport and Yellowknife Hydro (Environment Canada, 1969-1970). Mean annual air temperatures recorded are -5.5°C and -6.2°C for Yellowknife Airport and Yellowknife Hydro respectively (Brown, 1973; Burns, 1973; Judge, 1973). Winter minima consistently drop below -40.0°C and summer maxima often rise above 26.0°C (Environment Canada, 1970; Department of Transport, 1974). The mean annual range of monthly air temperature is approximately 43.0°C (Judge, 1973), while the mean surface temperature ranges between -1.8°C and $+1.5^{\circ}\text{C}$. Mean annual snowfall for Yellowknife is 109 cm (Judge, 1973). Permafrost is widespread but not continuous, ranging in depth from 0 to 60 metres.

The terrain consists predominantly of Precambrian Shield bedrock outcrop with pockets of glacial till, beach sediments and glaciofluvial deposits. Low lying areas are frequently occupied by small lakes, muskeg or peat bogs. Brown (1973) observed permafrost in unconsolidated sediments and bedrock covered by a mantle of overburden, but did not observe permafrost in exposed bedrock sites. Ground temperatures have been monitored at eight sites in the Yellowknife area. Of the eight, only three were located in exposed bedrock with very little surface vegetation.

The "Blackrock" site, located in a Precambrian greenstone formation, proved to be the most useful to this study because it offered the most comprehensive set of observations. A twelve-point thermocouple cable installed to a depth of 15.0 metres enabled temperatures to be recorded one to four times per month. The period of observation selected for comparison is October 1969 to December 1970.

Climate data were obtained for the same period from the Atmospheric Environment Service's monthly publication of meteorological summaries

(Environment Canada, October 1969 - December 1970). Yellowknife does not record incoming solar radiation, the closest observations being for Fort Simpson and Norman Wells. Incoming solar radiation data were interpolated from mean annual radiation maps published by Environment Canada (Burns, 1973). The remaining site characteristics and subsurface data were obtained from personal communications (M.W. Smith, R.J.E. Brown and A.S. Judge).

Table 1 presents the site-specific and subsurface properties used as inputs in MICRO. The initial array of ground temperatures was derived from data provided by Dr. R.J.E. Brown.

2.2 Test Results

Figures 3 and 4 show the agreement between observed and predicted ground temperature values for a twelve-month period. Initial results indicate that the thermal regime simulated by MICRO is a close approximation of observed conditions. In almost all cases, the model accurately predicts temporal trends in subsurface temperatures. Figure 3 shows the relationship between the predicted and observed pattern of frost penetration and thaw using the 0°C geotherm. During the period from October 1969 to July 1970 the predicted depth of the 0°C geotherm is within ± 0.3 metres of the observed depth. The predicted maximum frost penetration of 11.2 metres depth is reached in mid-July, while Brown observed a maximum frost penetration of 10.7 metres by late June and early July. The 5.0% difference between predicted and observed values represents a high level of accuracy. This small discrepancy could be due to several factors.

First, climate data are input in the form of monthly averages for the 15th of each month. Daily climatic conditions are interpolated by

Variable	Greenstone	Units	Source
Thermal Conductivity	0.0071	cal/cm/sec/ $^{\circ}$ C	Judge, personal communication
Thermal Diffusivity	0.0126	cm ² /sec	calculated
Volumetric Heat Capacity	0.56	cal/cm ³ / $^{\circ}$ C	Judge, personal communication
Porosity	0.2	% Volume	Brown (1973); Smith (1973)
Density	2.95	gm/cm ³	Judge, personal communication
Surface Albedo	0.17	Decimal Fraction	Smith (1975; 1977)
Surface Roughness	0.2	cm	Smith, personal communication
Snow Density	0.25	gm/cm ³	Smith (1977)
Site Wetness	0.1		Smith, personal communication

TABLE 1: Site specific surface, and subsurface thermal properties of the "Blackrock" site, Yellowknife.

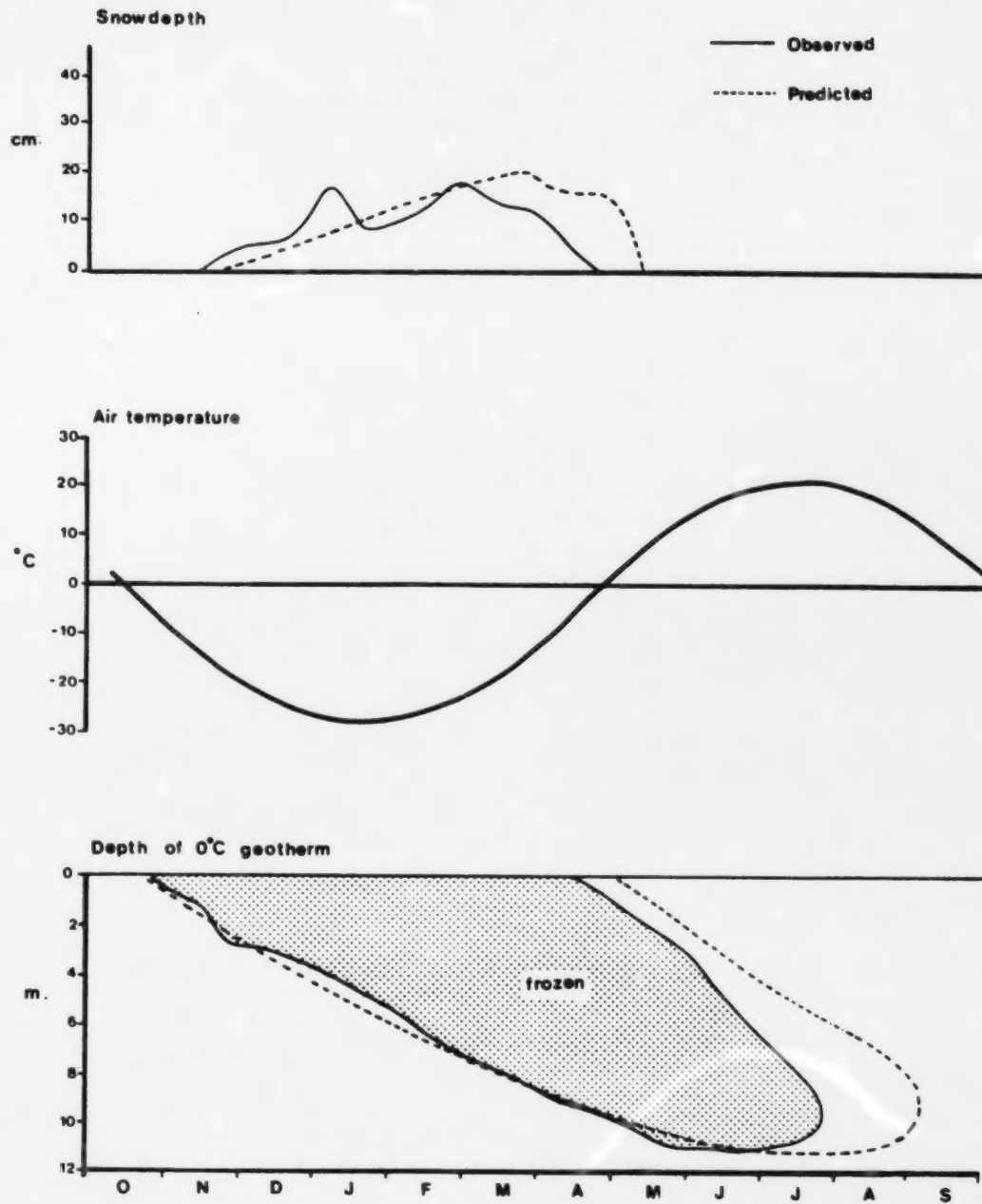


FIGURE 3: Predicted and observed thermal regimes, snowfall and air temperature for Yellowknife.

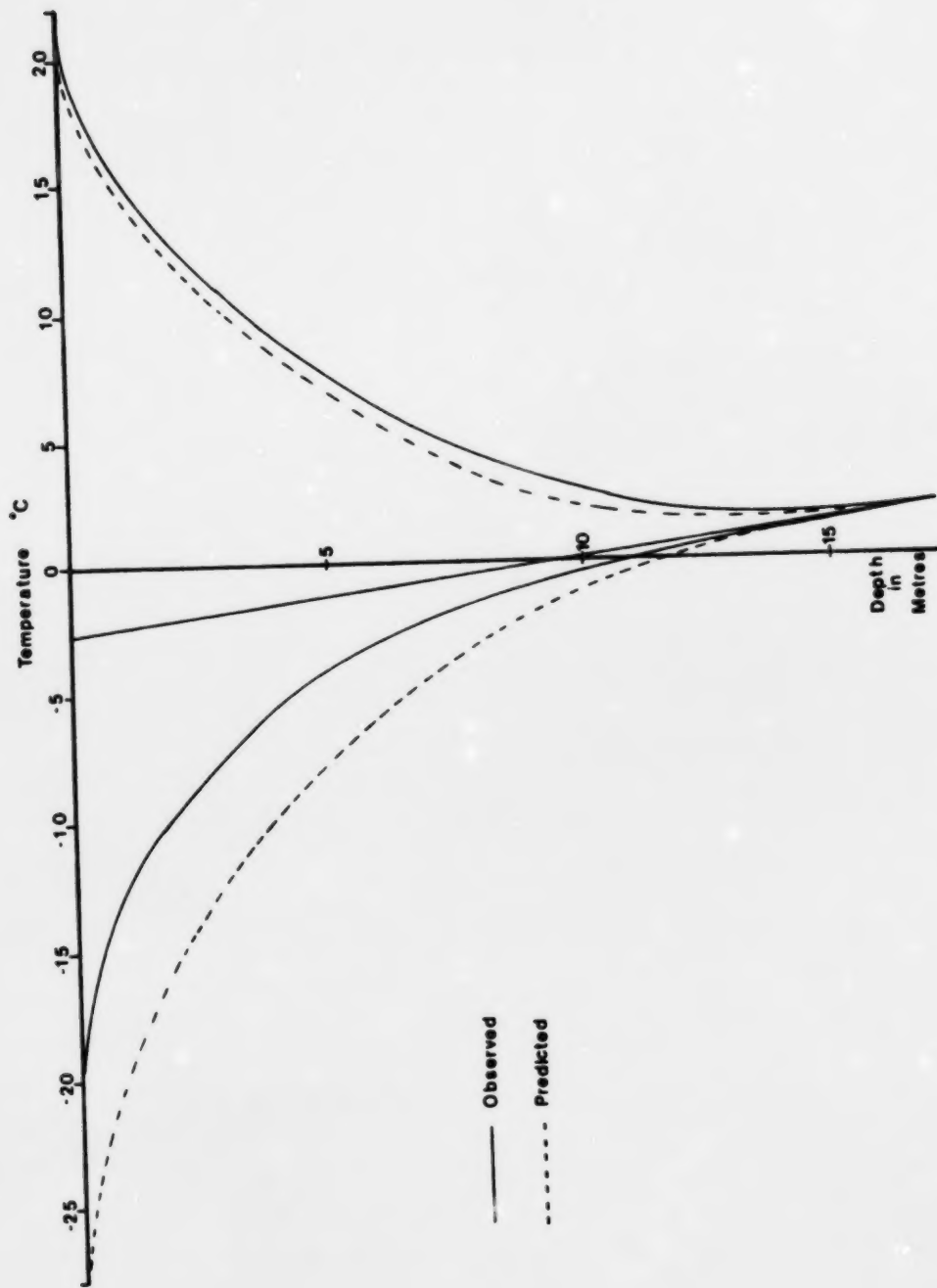


FIGURE 4: Predicted and observed temperature envelopes for Yellowknife.

the computer program, thus resulting in a statistical smoothing of data over the monthly period. This eliminates the effect of short-term climatic variations which may show up in the ground thermal regime. Similarly, snowfall is distributed over the monthly period and individual snowfall events are generalized. Also, the model does not accommodate changes in snowdepth resulting from drifting, sublimation and melting prior to snowpack ripening. Because of this, the predicted snowpack tends to be deeper and to last longer than the observed. The prolonged presence of snow and the greater accumulation result in a lag effect which, from Figure 3, appears to be from two to three weeks. This contributes to the predicted persistence of freezing conditions longer than observed. Once thaw is initiated, the predicted rate of thaw compares favourably with the observed rate.

Figure 4 compares the predicted temperature envelope with the observed. The predicted minimum temperatures are 2°C to 5°C colder than the observed, while maximum predicted temperatures are generally within 0.5°C to 1.0°C of the observed. The range of predicted temperature is slightly greater than the observed temperature range and generally cooler.

Figure 5 shows the temporal relationship between predicted and observed temperatures at depths of 1.0, 5.0 and 10.0 metres. For the two lower depths the predicted values show a strong agreement with observed values, while at 1.0 metre the relationship is not quite so good.

A lag in thaw penetration of approximately 7-8 days is visible at a depth of 1.0 metre, while at a depth of 5.0 metres the lag time is approximately 12-14 days. Predicted winter temperatures at a depth of 1.0 metre are up to 5.0°C colder than observed values, while summer predictions are within 1.0°C to 2.0°C of the observed. Apart from the

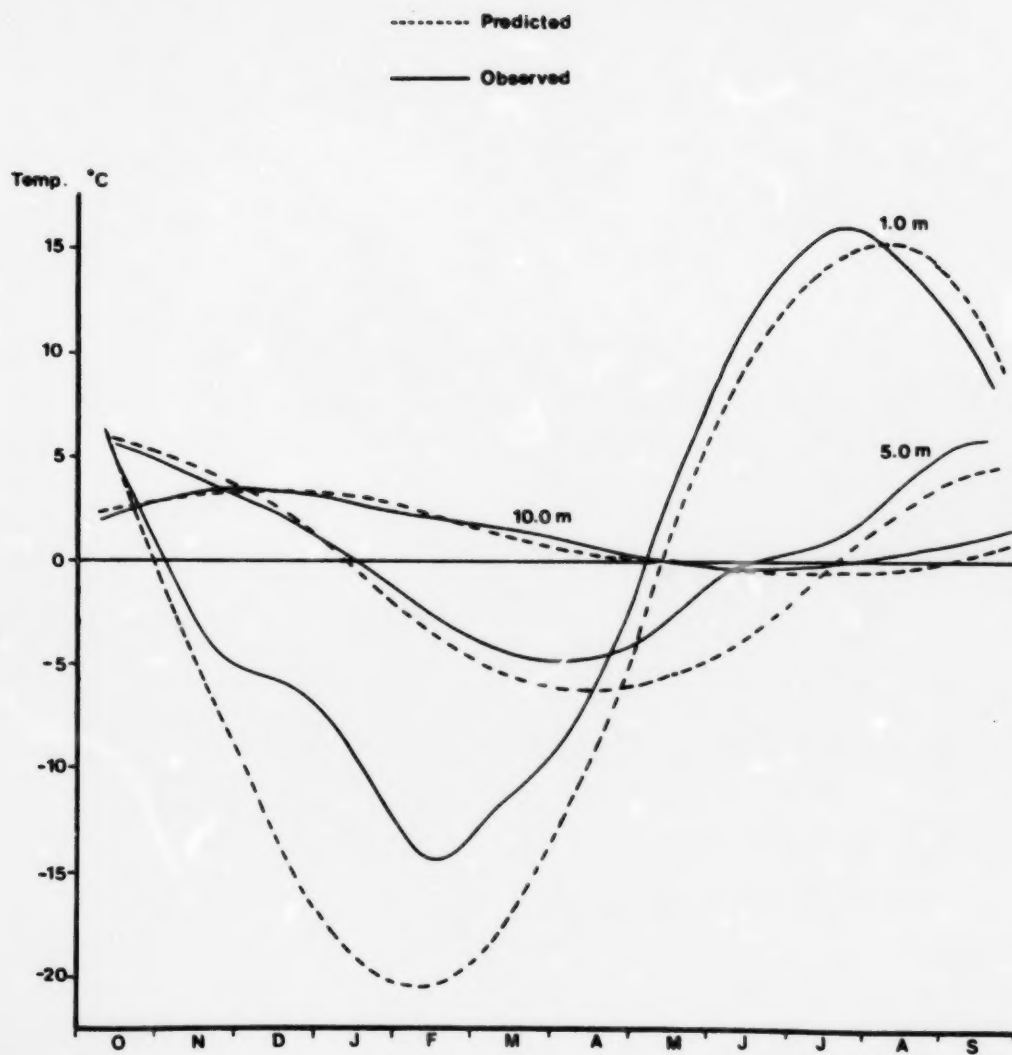


FIGURE 5: Predicted and observed temperatures at 1.0, 5.0, and 10.0 metre depths.

misrepresentation of snowdepths in the prediction, there appears to be no apparent explanation for the discrepancy between predicted and observed winter ground temperatures at a depth of 1.0 metre.

In conclusion, it is felt that the model is accurate to $\pm 5.0\%$ and is therefore a very useful predictive tool in bedrock thermal regime studies.

3.0 Simulation, Eagle Plain

This section of the paper is concerned with the prediction of surface energy and subsurface thermal regimes in the Eagle Plain Basin, Yukon Territory.

During reconnaissance field investigations conducted in the Eagle Plain in the summer of 1979, it was observed that bedrock and felsenmeer surfaces are dominant terrain components. In such an environment, bedrock thermal regimes are an important factor influencing local geomorphic processes.

3.1 Study Area

The Eagle Plain is an unglaciated intermontane basin, at an elevation of between 300 and 800 metres above sea level and occupying approximately 25,000 square kilometres in the northern Yukon Territory (Figure 6). The topography of the Eagle Plain consists of rolling hills with a maximum relief of approximately 470 metres and an average relief of 160 metres (Bostock, 1961).

The Laurentide ice sheet of the Wisconsin glaciation appears to have extended as far as the Richardson Mountains and the Peel River, which form the eastern and southeastern boundary of the area; however, there is no evidence of glaciation within the Eagle Plain itself

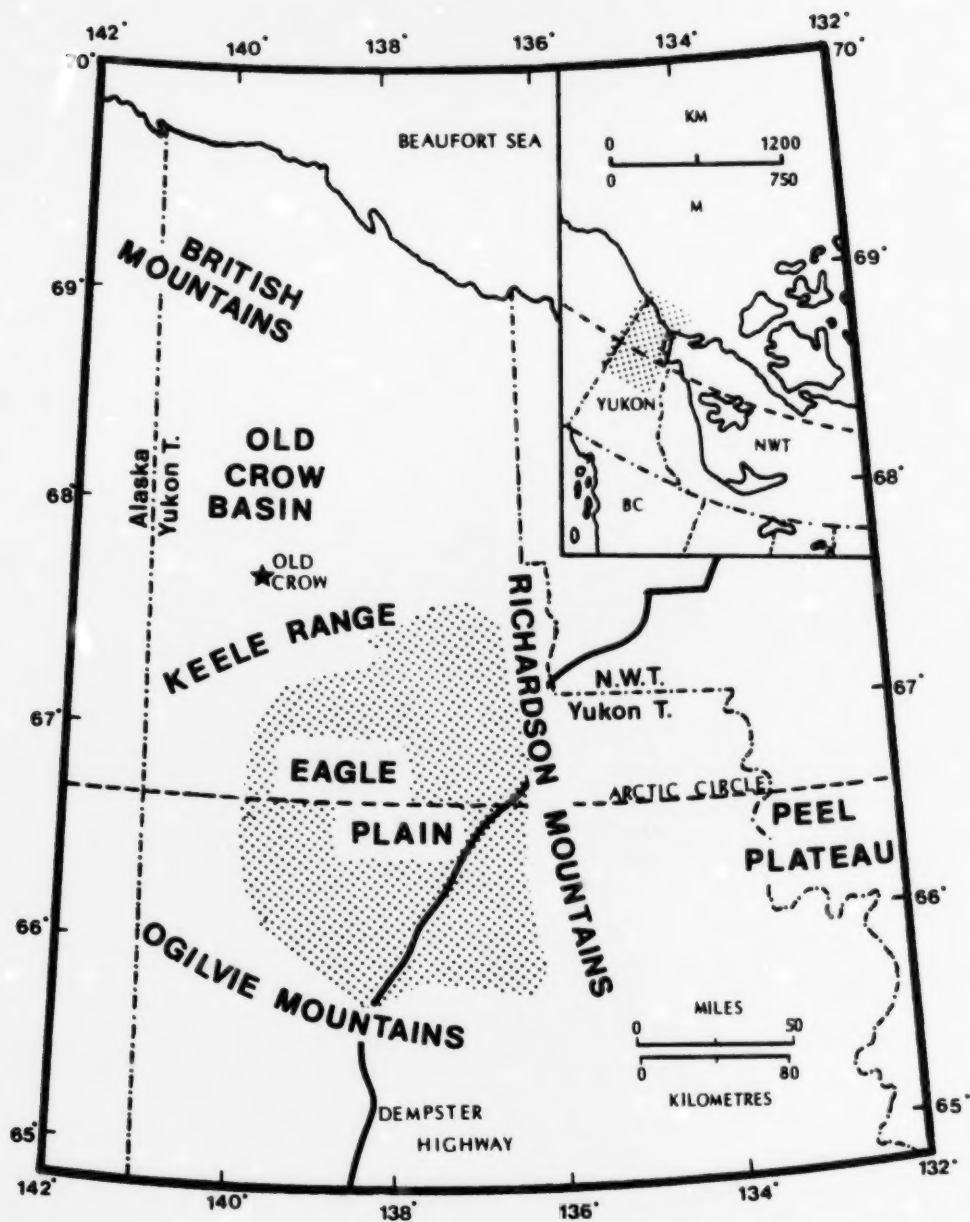


FIGURE 6: Location map of Eagle Plain, northern Yukon Territory.

(Hughes, 1969). This may be related to the aridity of the Eagle Plain region, resulting from the combination of an interior location flanked by mountain ranges (French, 1977).

The upland surfaces are characterized by an angular felsenmeer mantle, with steep-sided bedrock outcrops and tors. Significant gravel, sand and silt deposits occur in some of the larger river valleys. A thick accumulation of peat was observed by the author in a river section in the interior of the Eagle Plain. Various periglacial features (e.g. frost wedge polygons, patterned ground, ice lenses and beaded drainage) have been observed in valley bottom sediments, while upland rock surfaces display frost-shattered felsenmeer and expanded joint patterns.

The widespread distribution of these terrain features generally suggests the presence of continuous permafrost in the Eagle Plain (French, 1977). Judge (1973) reports permafrost to a depth of 90.0 metres with an observed mean surface temperature of -4.2°C .

The Eagle Plain experiences a cold continental climate with a mean annual air temperature between -5.0°C and -10.0°C and approximately 25.0 to 30.0 centimetres of precipitation. Sporadic climate observations are available for various points along the Dempster Highway, but are not adequate for input into MICRO. Dawson City Airport, approximately 250 kilometres southwest, is the closest meteorological station reporting sufficient climate data. Mean annual air temperatures at Dawson are 2°C to 3°C warmer than at Eagle Plain. Winter temperatures are consistently 5°C warmer, while summer temperatures vary only by 1°C to 2°C . Dawson weather for the period of October 1976 to December 1977 was used as the initial climate data input for simulation modeling (see Table 2).

DAWSON AIRPORT; (latitude: 64° 04'N longitude: 139° 26'W)

Climatic Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature (°C)	-25.3	-19.8	-11.3	-.3	8.2	12.1	16.0	13.3	7.9	-15.6	-23.6	-24.2
Precipitation												
Total (in mm)	11.6	5.1	4.6	.2	14.7	43.0	23.0	11.0	60.0	23.0	19.3	21.5
Rain	Tr	-	-	-	14.7	43.0	23.0	11.0	59.0	3.3	-	-
Snow	11.0	5.1	4.6	.2	-	-	-	-	1.0	20.0	19.3	21.5

Mean Annual Temperature: -5.2°C

Total Precipitation: 23.7 cm.

OLD CROW AIRPORT; (latitude: 67° 34'N longitude: 139° 50'W)

Climatic Variable												
Temperature (°C)						9.7	15.9	10.5		-8.6	-20.6	-28.0
Precipitation												
Total (in mm)						5.2	8.4	22.0		27.0	20.0	12.3
Rain						5.2	8.4	22.0		4.0	-	-
Snow						-	-	-		23.0	20.0	12.3

TABLE 2: Climate data, Dawson and Old Crow Airports.

The presence of extensive areas of rock rubble and felsenmeer, combined with the knowledge that the area has experienced cold non-glacial conditions for much of the late Pleistocene until the present, leads one to conclude that climate has exerted a fundamental control over rock weathering processes. It is widely believed, for example, that frost shattering and repeated freeze-thaw cycles are causes of rock weathering in periglacial climates (e.g. Battle, 1960; Fahey, 1979; Tricart, 1959; Washburn, 1973, p. 61; Wiman, 1963). However, it has also been suggested that hydration shattering may be the dominant rock weathering process in cold climates (Goldich, 1938; White, 1976). The efficacy of frost shatter and freeze-thaw weathering is not a problem addressed in this paper. Nevertheless, the prediction of thermal regimes, including the simulation of frost penetration and freeze-thaw cycles, could contribute valuable information to an understanding of the range of geomorphic processes active in this area.

3.2 Input Data

In contrast to the Yeliowknife area, there are very few climatic and subsurface thermal data available for the Eagle Plain. Judge (1973) presents thermal observations from a single well and from another well in the Anderson Plains; both areas display some of the same rock formations. The thermal properties of the Imperial Formation and Canol Formation are listed. These data, plus information obtained through personal communication form the basis of the ground thermal input into MICRO (Table 3). Other site-specific information (e.g. albedo, surface roughness, snow density) was derived from either Smith (1977) or personal communication (Table 3).

Since Whitehorse is the only meteorological station in the Yukon Territory recording incoming solar radiation, it was necessary to estimate

Variable	Limestone	Sandstone	Units	Source
Thermal Conductivity	0.004	0.0036	cal/cm/sec/ ^o C	Judge (1973), personal communication
Thermal Diffusivity	0.0063	0.0063	cm ² /sec	Calculated
Volumetric Heat Capacity	0.63	0.57	cal/cm ³ / ^o C	Judge (1973), personal communication
Porosity	1.5	3.0	% Volume	Judge (1973)
Surface Albedo	0.22	0.22	Decimal Fraction	Smith (1977) Davies (1967)
Surface Roughness	0.2	0.2	cm	Smith, personal communication
Snow Density	0.23	0.23	gm/cm ³	Smith (1977) Williams (1957)
Site Wetness	0.1	0.1		Smith, personal communication

TABLE 3: Site specific surface and subsurface thermal characteristics for the Eagle Plain.

radiation input values using a computer model developed by Fuggle (1970). This model calculates incoming direct short-wave radiation on slopes from inputs of latitude, angle of declination of the sun, atmospheric transmissivity, slope azimuth, and slope gradient; a listing of the program is presented in Fuggle(1970). This program can be used to estimate incoming solar radiation for flat surfaces by assigning slope azimuth and slope gradient the value of zero. This procedure was used to estimate atmospheric transmissivity values to correspond with known incoming solar radiation data for Whitehorse during the period from October 1976 to December 1977. The estimated transmissivity values were then input into Fuggle's model, together with data corresponding to the Eagle Plain, to estimate incoming solar radiation values to be used in MICRO. This methodology assumes no difference in atmospheric transmissivity between Whitehorse and Eagle Plain.

The same program was also used to estimate incoming solar radiation on north and south-facing slopes of 10° and 30° . These estimated solar radiation values were used, together with Dawson weather and previously discussed site-specific surface and subsurface thermal properties, to investigate the effect of rock type, slope and aspect on the bedrock thermal regime. Table 4 presents the range of site characteristics examined for Eagle Plain.

3.3 Test Results

The estimated mean monthly values of incoming solar radiation (in langley's/day) for the Eagle Plain during the period from October 1976 to December 1977 are presented in Table 5. Also included are average monthly values of declination and transmissivity.

As might be expected, Table 5 shows that south-facing slopes receive more direct incoming solar radiation than flat and north-facing slopes, and

ROCK LITHOLOGY	SLOPE ASPECT (in degrees)	SLOPE GRADIENT (in degrees)	MAXIMUM DEPTH OF THAW (in metres)
Limestone	—	0.0	3.28
	180.0 (S)	10.0	3.51
	180.0 (S)	30.0	3.90
	360.0 (N)	10.0	2.73
	360.0 (N)	30.0	1.70
Sandstone	—	0.0	2.95
	180.0 (S)	10.0	3.17
	180.0 (S)	30.0	3.61
	360.0 (N)	10.0	2.58
	360.0 (N)	30.0	1.65

TABLE 4: List of the site conditions simulated using MICRO, and corresponding maximum active layer depths.

EAGLE PLAIN: 66° 00' N

Month	Declination	RS*	TR**	Estimated RS values on slopes			
				South		North	
				10'	30'	10'	30'
September	3.1°	218	76	263.0	363.0	133.0	1.7
October	- 8.4°	130	83	118.0	210.0	22.0	0.0
November	-18.4°	45	87	22.0	50.0	0.0	0.0
December	-23.2°	30	94	26.0	7.1	0.0	0.0
January	-21.3°	26	92	19.1	48.3	0.0	0.0
February	-13.1°	103	89	110.0	209.8	2.0	0.0
March	- 2.5°	214	85	254.1	384.3	93.3	0.0
April	9.6°	372	85	484.0	600.5	310.0	99.0
May	18.8°	484	79	581.0	641.3	458.0	279.6
June	23.2°	550	70	536.0	566.0	448.0	307.0
July	21.5°	444	70	506.0	545.0	410.8	266.0
August	14.0°	407	75	438.0	516.0	309.0	141.9
September	3.1°	218	76	263.0	363.1	133.0	1.7
October	- 8.4°	118	80	115.0	195.4	21.8	0.0
November	-18.4°	41	85	21.0	48.0	0.0	0.0
December	-23.2°	20	90	24.1	6.6	0.0	0.0
Total	—	3420	—	3780.0	4753.6	2341.9	1098.0
Mean	—	213	82	236.0	297.0	146.5	69.0

RS* - Solar Radiation measured in langley/day for a flat surface.

TR** - Atmospheric Transmissivity estimated using Fuggle (1970) measured as a percent.

All RS values are measured in langley/day.

TABLE 5: Estimated Solar Radiation, and Atmospheric Transmissivity values for the Eagle Plain, 1976-1977.

that the steeper the slope, the greater the intensity. The converse applies to north-facing slopes. Also, peak solar radiation occurs during May and June, while minimum values are observed during December and January.

Figure 7(a) displays the predicted thermal regime for a horizontal limestone site at $66^{\circ} 00' N$, approximating the southern part of the Eagle Plain. The model predicts the presence of permafrost with a maximum depth of seasonal thaw of 3.3 metres. The temperature envelope illustrated in Figure 8(a) confirms the active layer depth to be between 3.3 and 3.4 metres and is generally skewed toward the colder temperatures. Brown (1973) observed active layer depths to 2.2 metres in bedrock at Devon Island in the Canadian Arctic. Thus the predicted active layer depths at the Eagle Plain do not seem unreasonable.

Figures 7(b) and 8(b) show the predicted thermal regime and temperature envelope for sandstone. The model predicts an active layer depth of 3.0 metres, slightly less than for the limestone. Since the thermal characteristics of both the limestone and sandstone formations are quite similar (see Table 3) it is not surprising that the predicted thermal regimes vary by only 0.3 metre or 10.0%. This slight difference probably reflects the porosity values used in the prediction, since they determine the latent heat terms.

In limestone, thaw begins in early May and freezeback starts in early October; in sandstone, thaw starts in mid-May and freezeback commences in late October. Also, the model predicts slight variations in snow accumulation on different rock types. In the Yellowknife test, snowmelt and initiation of thaw were identified as problems in the predictive model. Given the results of the Yellowknife simulation, one might expect that both

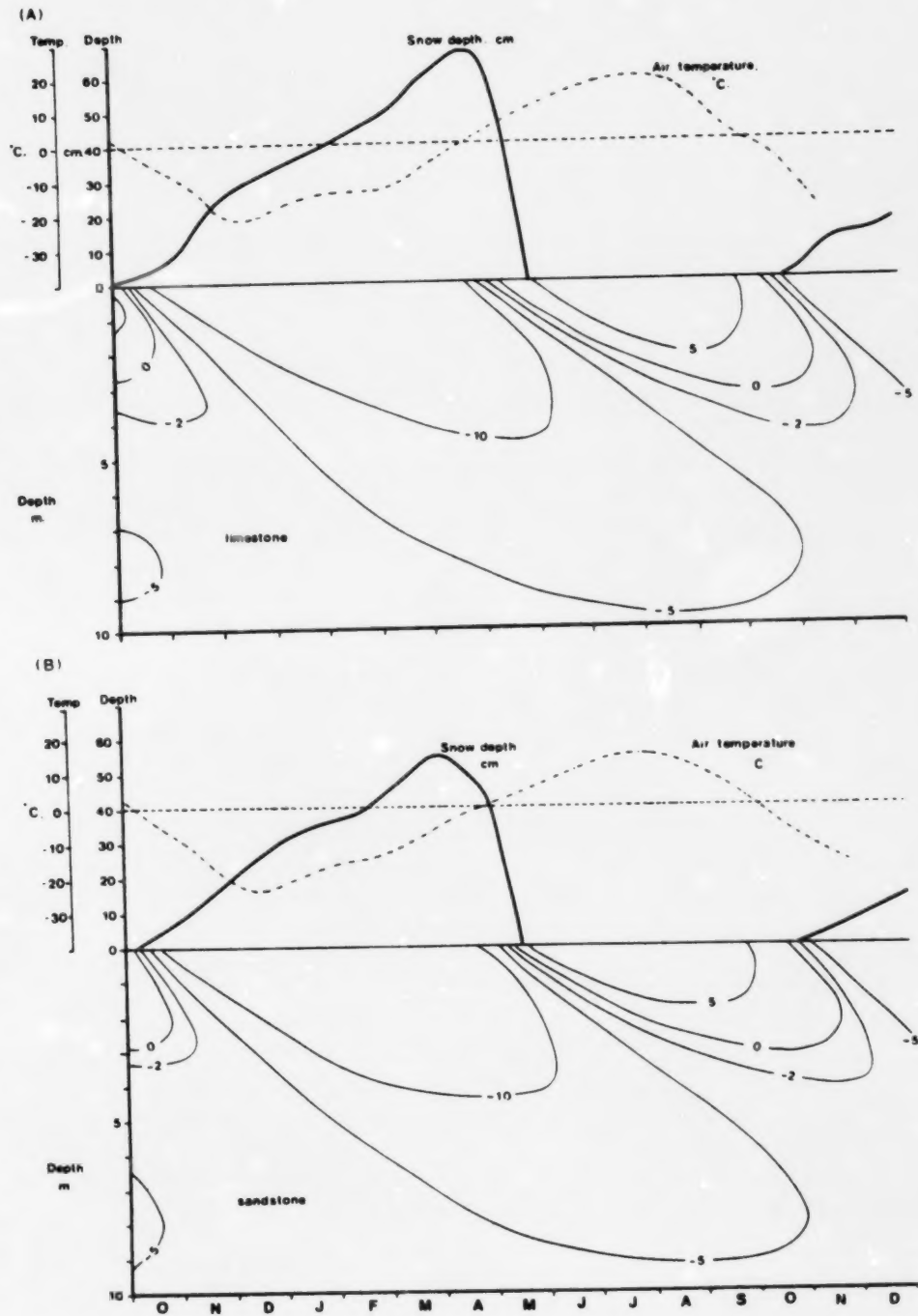


FIGURE 7: Predicted thermal regime for horizontal limestone and sandstone surfaces in the Eagle Plain.

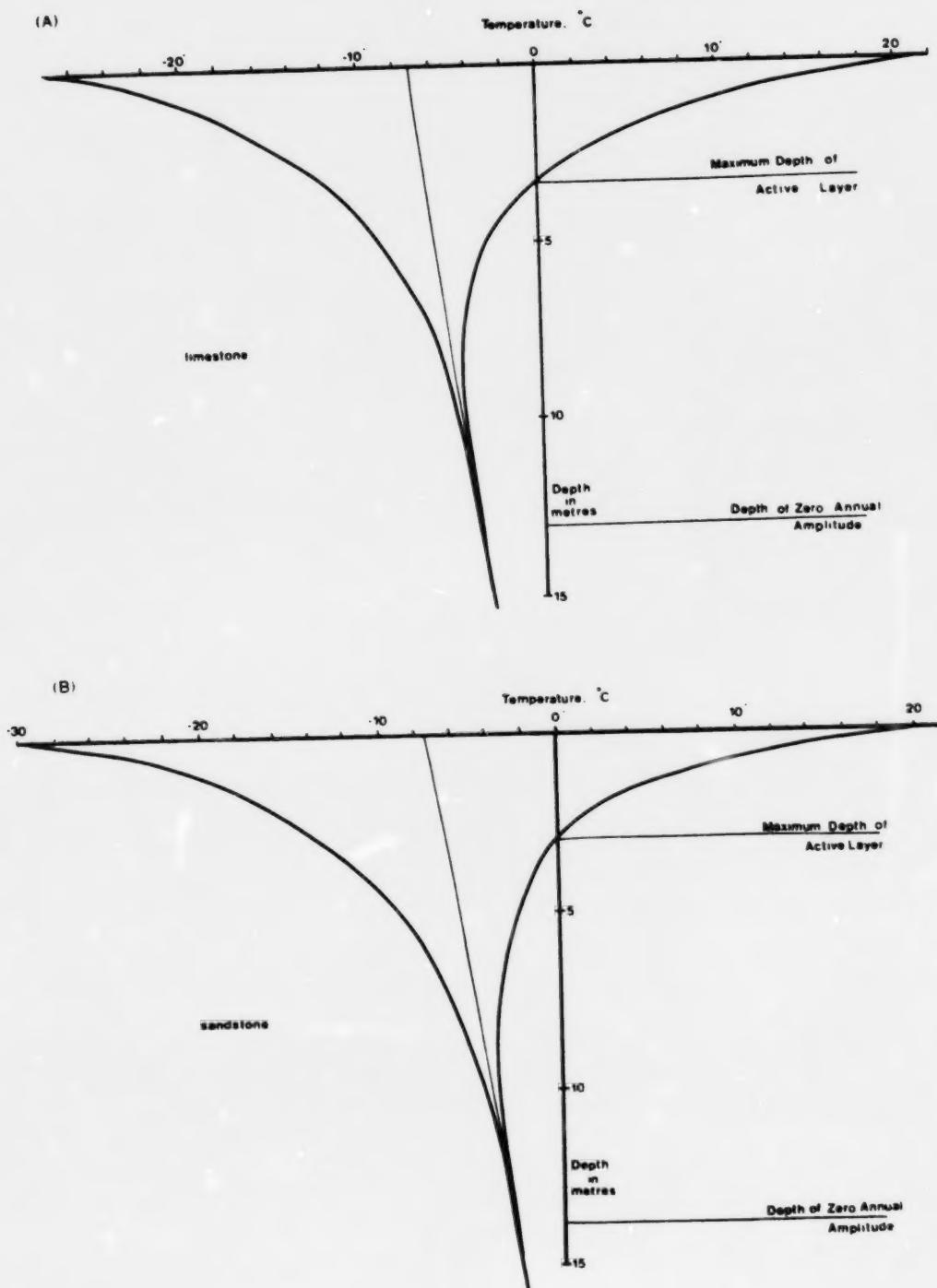


FIGURE 8: Predicted thermal envelopes for horizontal limestone and sandstone surfaces in the Eagle Plain.

snowmelt and thaw would occur sooner than predicted in the Eagle Plain.

The range of ground thermal regimes which occurs with changing slope aspect and gradient for the two rock types is illustrated in Figures 9 and 10.

For south-facing slopes, in both the limestone and sandstone, the most notable feature is the deeper thaw penetration and the longer thaw season. On 10° slopes, the 0°C geotherm is 20 cm to 30 cm deeper than for a horizontal surface. The freezing period is shorter and the depth of penetration of cold thermal waves is shallower. Thaw starts in late April in both the limestone and sandstone and freezeback commences in early to mid-October and is complete by early November.

On 30° slopes, the active layer reaches 4.0 metres in depth in the limestone and 3.8 metres in the sandstone. In both cases, thaw begins in late April. Freezeback commences in the second week of October and is complete by November 22 in sandstone and November 27 in limestone. Cold thermal waves initiated in January and February reach their maximum depth by July; their effect in this situation is not as deep as in the case of flat or north-sloping surfaces.

Figure 10 presents the predicted ground thermal regimes of north-facing slopes of 10° and 30° . As might be expected, north-facing slopes receive considerably less direct incoming solar radiation. This results in generally cooler ground temperatures. It follows that 10° north-sloping surfaces display shallower active layers and shorter thaw periods. Predicted ground temperatures in the winter are cooler at all depths. The thaw in limestone is predicted to start in mid-May and to reach a maximum depth of 2.7 metres in September. Freeze-up, beginning in early October, is predicted to be complete by the 22nd of the month. Similar conditions appear to be

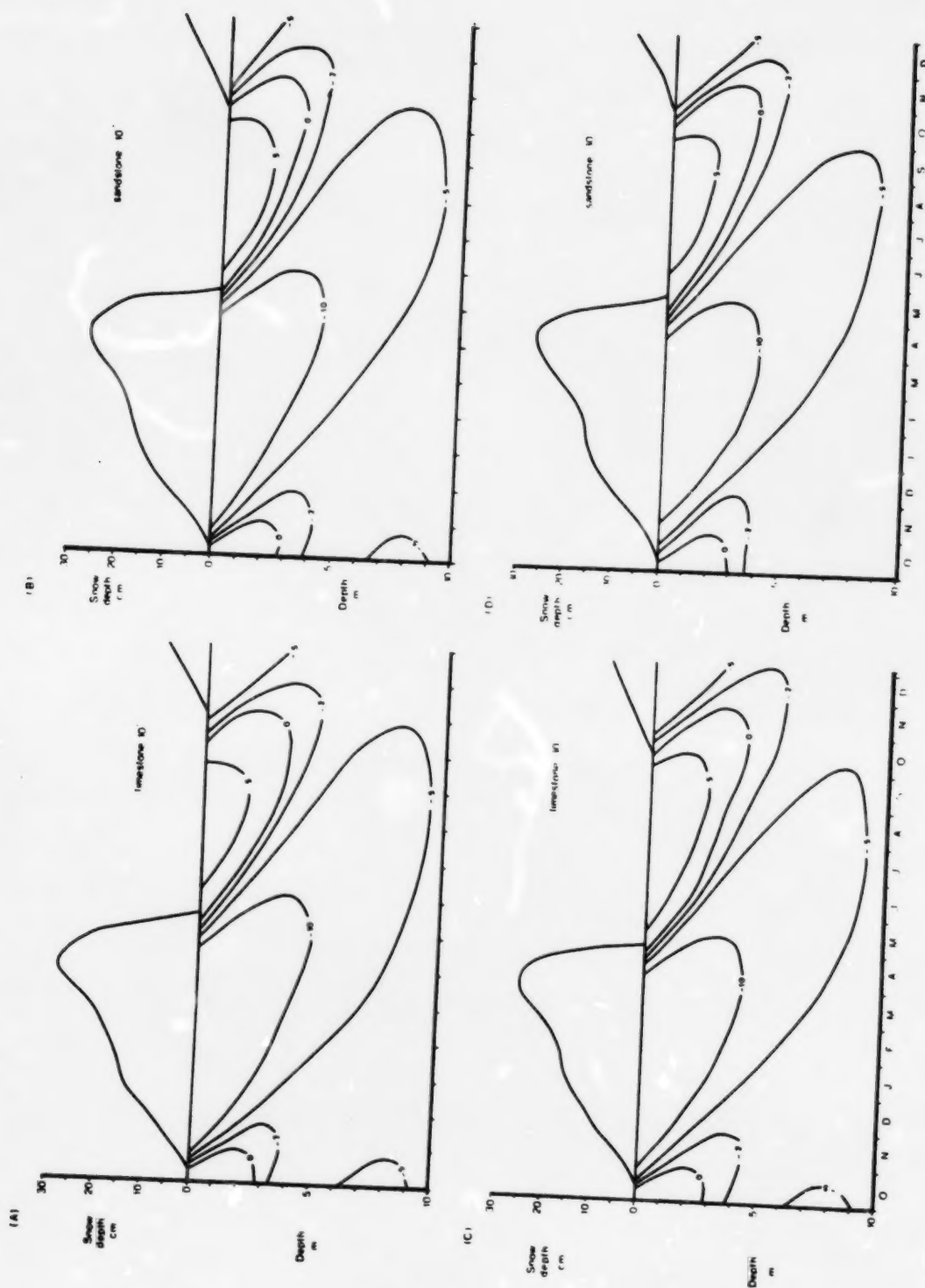


FIGURE 9: Predicted thermal regimes for south-facing limestone and sandstone bedrock slopes of 10 and 30 degrees, Eagle Plain.

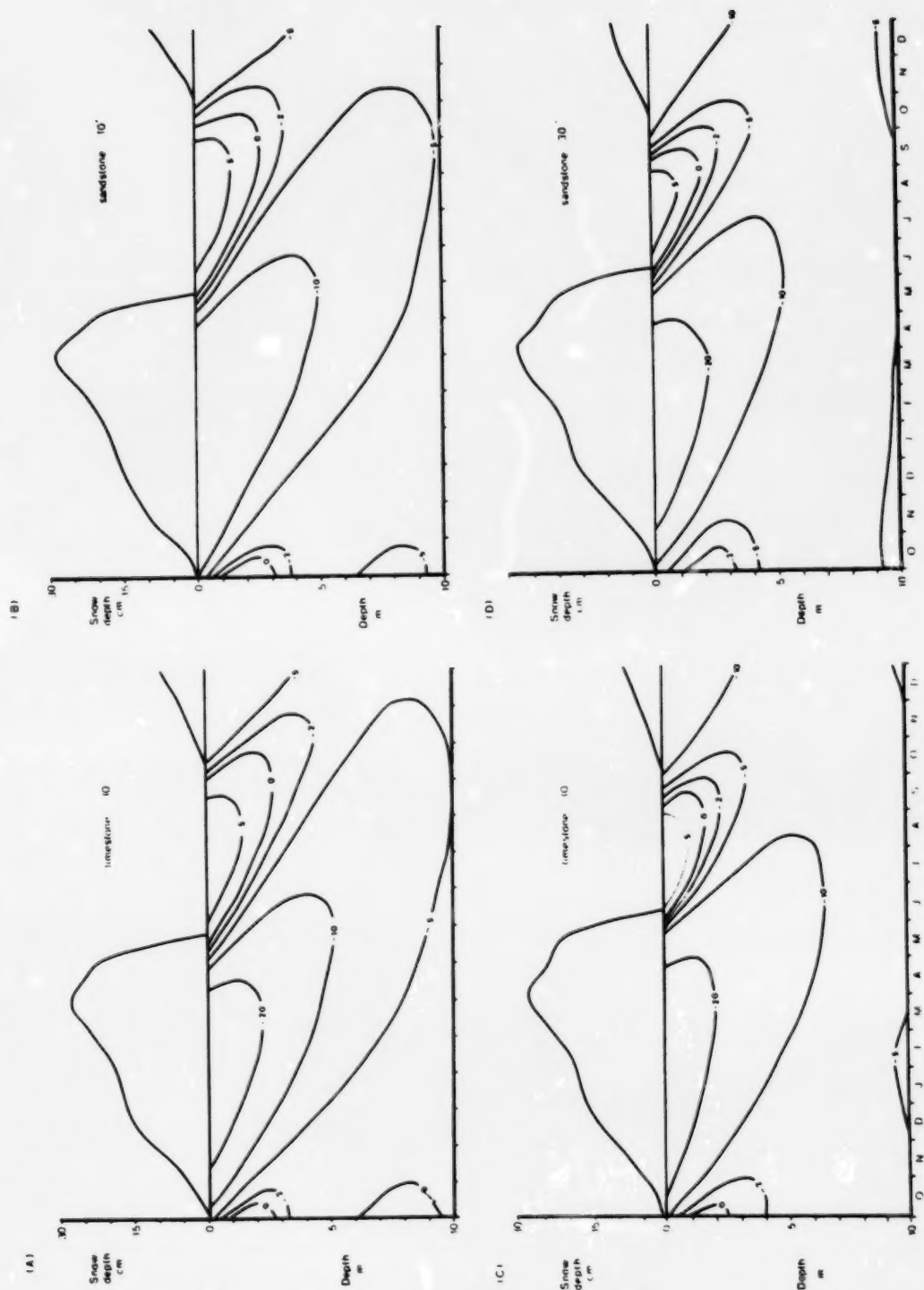


FIGURE 10: Predicted thermal regimes for north-facing limestone and sandstone bedrock slopes of 10 and 30 degrees, Eagle Plain.

predicted for the sandstone, although thaw depth is slightly shallower.

Finally, the thermal regimes of north-facing slopes of 30° are significantly colder than other simulated conditions. Maximum predicted depth of seasonal thaw is 2.6 metres in limestone and 3.0 metres in sandstone. In both cases, thaw commences in early June, reaching its maximum depth in the last week of August. Freezeback begins in early September and is complete by the 15th to the 20th of the same month. At depths of 9.0 and 10.0 metres, the temperature is 1.2°C colder than in other simulations.

3.4 Discussion

The theoretical predictions reveal some of the basic ground thermal and surface energy regime characteristics of two rock lithologies in the Eagle Plain. MICRO predicts the presence of permafrost in all cases, with seasonal thaw extending up to 3.5 metres in depth. Cold thermal waves, corresponding to the cold climatic conditions of January and February penetrate to depths of 11.0 to 13.0 metres. For practical reasons, the predicted thermal regimes are restricted to the upper 15.0 metres. This approximate depth is thought to correspond to the depth of zero annual amplitude (Judge, 1973), and therefore, is thought to be a realistic lower limit for the simulation.

The thermal properties of the two rock lithologies expressed in terms of thermal conductivity, volumetric heat capacity and thermal diffusivity are very similar (see Table 3). However, by virtue of their high conductivity and diffusivity characteristics relative to soils, rocks are more sensitive and respond faster to thermal disturbances than soils. The lower porosity values and the relative dryness of rock in comparison

with soil is also a factor resulting in a higher thermal sensitivity. In particular, the lower porosity of limestone (1.5%) relative to sandstone (3.0%) is possibly an important factor in the difference in thermal response in this study (e.g. the difference in thaw depth and period between sandstone and limestone). Therefore, subtle differences in lithology may result in significantly different thermal regimes. This might be reflected in different felsenmeer characteristics (size, angularity, thickness, etc.) on limestone and sandstone bedrock topographies, in the distribution of patterned ground phenomena, and in rates of mechanical weathering.

The effect of slope aspect and gradient is also demonstrated in this portion of the study. Obviously, south-facing slopes receive more direct incoming short-wave radiation than horizontal and north-sloping surfaces. This results in warmer surface temperatures during periods of peak radiation (diurnal and seasonal), and in nominal surface temperature differences during periods of minimum radiation. Thus, the predicted increased thaw on south-facing slopes during summer months is the correct geomorphic response. This may be reflected in increased mass wasting and solifluction on south-facing slopes.

Furthermore, permafrost may penetrate to greater depths in north-facing slopes, where lower surface temperatures result in a generally colder ground thermal regime and a shallow penetration of seasonal thaw. The number of freeze-thaw cycles on north-facing slopes would probably be restricted to the annual cycle, and the depth of freeze-thaw would compare with the active layer. Conversely, horizontal and south-facing surfaces appear to experience a greater range of temperature and a greater number of short-term freeze-thaw cycles. This might suggest that frost weathered debris is better developed on south-facing slopes in the Eagle Plain since such slopes are subject to

more frequent freeze-thaw events. On the other hand, intensity of the freeze-thaw cycle may be more important than the frequency.

All these factors (porosity, frost intensity, freeze-thaw cycles and temperature range) have a direct relationship to the rate and intensity of frost shattering. The presence of snow, as a source of moisture, is also an important variable relating to the effectiveness of frost shatter. The predicted colder temperatures and prolonged snow-patch presence of north-facing slopes may also relate to the felsenmeer and rock rubble surfaces in the Eagle Plain. Nivation and snow-patch weathering is acknowledged as an important weathering process in periglacial environments (Thorn, 1979; St-Onge, 1969). Also important in bedrock areas is the presence and movement of ground water in faults and fissures in large rock bodies. The freezing of pore and fissure water is an important mechanical weathering process and also influences the thermal regime.

4.0 Conclusion

The numerical simulation model MICRO demonstrates a level of accuracy of $\pm 5.0\%$ for the prediction of bedrock thermal regimes. The Yellowknife test shows that predicted values accurately simulate temporal variation in bedrock temperatures with changing climatic conditions. The greatest variation between predicted and observed temperature values occurred during winter at shallow depths. At all other times during the simulation, predicted values showed good agreement with observed conditions. The predicted snowdepths varied significantly from observed snowdepths. This is a function of the monthly input procedure and the surface processes (e.g. drifting of snow, sublimation, partial melting), which were not incorporated into the simulation.

The accuracy and validity of predicted values depend heavily upon the accuracy of data input. Apparent weaknesses in the model are primarily associated with the accumulation and ablation of the snowpack. The model tends to predict snowdepths greater than observed and simulates snowfall as a continuous event. The program also ignores the effect of drifting snow. Furthermore, the snow ripening algorithm tends to prolong the presence of snow and delay thaw. This initiates a lag in thaw penetration and results in deeper penetration of predicted seasonal frost (e.g. Yellowknife simulation).

It is expected that the accuracy of prediction would improve if daily weather data were used as input. Monthly climate inputs result in a statistical smoothing of predicted values, effectively reducing the impact of short-term climatic events and reducing the sensitivity of the simulation. If snowdepth data had been directly input into the program, the level of accuracy of prediction would have been higher. This was not done in this study however, since an objective was to make the Yellowknife and Eagle Plain tests as comparable as possible.

This study suggests that bedrock thermal regimes are very sensitive to variations of the surface energy balance. Natural or man-induced modification of the surface energy regime is likely to result in significant variations in the subsurface thermal regime. The impacts of thermal disturbances in a bedrock environment are not immediately apparent, as in the case of ice-rich soils, but are considerably more subtle and are a function of longer-term processes. If temperature is assumed to be a factor influencing mechanical weathering, changes in the bedrock thermal regime will certainly affect both the weathering process and the end product.

In the Eagle Plain, the nature, extent and distribution of felsenmeer deposits, patterned ground and other geomorphic phenomena, may be related to variations in the bedrock thermal regimes (and hence frost susceptibility) of the different rock types and site characteristics (e.g. aspect, angle of slope, etc.). The modeling approach may be of some use, therefore, in explaining the nature and distribution of these phenomena.

5.0 REFERENCES

- Battle, W.R.B., 1960, Temperature observations in bergschunds and their relationship to frost shattering, in: Norwegian Cirque Glaciers, W.V. Lewis (ed), Royal Geographical Society, London, 83-95.
- Bostock, H.S., 1961, Physiography and resources of the Yukon, Canadian Geographical Journal, 63, 4, 112-119.
- Brown, R.J.E., 1967, Permafrost investigations in British Columbia and Yukon Territory, Technical Paper 253, Division of Building Research, National Research Council of Canada, 43 pp.
- Brown, R.J.E., 1970, Permafrost in Canada: its influence on northern development, University of Toronto Press, 234 pp.
- Brown, R.J.E., 1973, Influence of climatic and terrain factors on ground temperatures at three locations in the permafrost region of Canada, in: Permafrost, North American contribution to the Second International Conference on Permafrost: July 1973, 27-34.
- Brown, R.J.E., 1978, Permafrost, in: Hydrologic Atlas of Canada, Environment Canada, Ottawa, Plate 32; map and explanatory notes.
- Brown, R.J.E., and W.O. Kupsch, 1974, Permafrost Terminology, Technical Memorandum No. 111, Associate Committee on Geotechnical Research, National Research Council of Canada, 62 pp.
- Burns, B.M., 1973, The Climate of the Mackenzie Valley - Beaufort Sea, Volumes 1 and 2, Climatological Studies No 24, AES, Toronto, 227 pp., 239 pp.
- Cook, F.A., and V.G. Raiche, 1962, Freeze-thaw cycles at Resolute, N.W.T., Geographical Bulletin, No 18, 64-78.

- Davies, J.A., and C.D. Allen, 1973, Equilibrium, potential and actual evaporation from cropped surfaces in Southern Ontario, Journal of Applied Meteorology, 12, 649-657.
- Fahey, B.D., 1973, An analysis of diurnal freeze-thaw and frost heave cycles in the Indian Peaks region of the Colorado Front Range, Arctic and Alpine Research, Vol. 5, No. 3, Part 1, 1973, 269-281.
- French, H.M., 1977, Permafrost and terrain report: Aquitaine Alder site, Eagle Plain, Yukon Territory (65° 52' N, 136° 52' W). Consultants Report, Aquitaine of Canada Ltd., Calgary, 12 pp.
- Garnier, B.J. and A. Ohmura, 1968, A method of calculating the direct shortwave radiation income of slopes, Journal of Applied Meteorology, Vol. 11, 1968, 796-800.
- Gold, L.W., 1967, Influence of surface conditions on ground temperature, Canadian Journal of Earth Science 4: 199-208.
- Gold, L.W., G.H. Johnston, W.A. Slusarchuk and L.E. Goodrich, 1972, Thermal Effects in Permafrost, Division of Building Research, National Research Council of Canada, Technical Paper 376, 15 pp.
- Gold, L.W. and A.H. Lachenbruch, 1973, Thermal conditions in permafrost - a review of North American literature, Permafrost; North American Contribution, Second International Permafrost Conference, Yakutsk, USSR, National Academy of Science, Pub. No. 2115, 3-25.
- Goldich, S.S., 1938, A study of rock weathering, Journal of Geology 46, 17-58.
- Harry, D.G., 1979, A theoretical approach to geocryological analysis and permafrost stratigraphy, (unpublished) Ph.D. Seminar II; Department of Geography, University of Ottawa, 73 pp.

- Hughes, O.L., 1969, Surficial geology of Northern Yukon Territory and District of Mackenzie, N.W.T., Geological Survey of Canada, Paper 69-36, 11 pp.
- Ingersoll, L.R., O.J. Zobel and A.C. Ingersoll, 1948, Heat Conduction, with Engineering and Geological Applications, McGraw Hill Book Company Inc., New York, Toronto, London, 278 pp.
- Jacobs, C.A. and P.S. Brown, 1973, An investigation of the numerical properties of the surface heat balance equation, Journal of Applied Meteorology, 12; 1069-72.
- Judge, A.S., 1973, "The Thermal Regime of the Mackenzie Valley, Observations of the Natural State", Environmental-Social Committees, Northern Pipelines' Task Force on Northern Oil Development, Report No. 73-38, 177 pp.
- Lachenbruch, A.H., 1959, Periodic heat flow in stratified medium with application to permafrost problems, Bulletin, United States Geological Survey, 1083-A, 36 pp.
- Lachenbruch, A.H., 1968, Permafrost, in: Encyclopedia of Geomorphology, ed. R.W. Fairbridge, Reinhold Book Co., New York, 833-8.
- Lewkowicz, A.G., 1978, Permafrost prediction: an evaluation of computer modelling for the discontinuous zone, (unpublished) Ph.D. Seminar II; Department of Geography, University of Ottawa, 54 pp.
- Martin, H.L., 1973, Eagle Plain Basin, Yukon Territory, in: The Future Petroleum Provinces of Canada, ed. R.G. McCrossan, Canadian Society of Petroleum Geology, Calgary, Alberta, 1973, 275-315
- Meteorological Branch Air Services, D.O.T., 1974, The Climate of Canada, Information Canada, Ottawa, 74 pp.

- Myrup, L.O., 1969, A numerical model of the urban heat island, Journal of Applied Meteorology, 8, 908-918.
- Nakano, Y. and J. Brown, 1972, "Mathematical modelling and validation of the thermal regimes in tundra soils, Barrow, Alaska", Arctic and Alpine Research, 4, 19-38.
- Outcalt, S.I., 1971, "A numerical surface climate simulator", Geografiska Annaler, 3, 379-392.
- Outcalt, S.I., 1972, "The development and application of a simple digital surface climate simulator", Journal of Applied Meteorology, 11, 629-656 pp.
- Outcalt, S.I., 1973, "A brief introduction to synthetic climatology and deterministic modeling strategy", Climatological Bulletin No. 14, McGill University, Montreal.
- Outcalt, S.I., C. Goodwin, G. Wellar and J. Brown, 1975, Computer simulation of the snowmelt and soil thermal regime at Barrow, Alaska, Water Resources Research, 11, 709-715.
- Sellers, W.D., 1965 (1969 ed), Physical Climatology, The University of Chicago Press, Ltd., London, 272 pp.
- Smith, M.W., 1975, Microclimatic influences on ground temperatures and permafrost distribution, Mackenzie Delta, N.W.T., Canadian Journal of Earth Science, Vol. 12, No. 8, 1421-1438.
- Smith, M.W., 1975, Numerical simulation of microclimatic and active layer regimes in a high arctic environment, Indian and Northern Affairs, Arctic Land Use Research, 74-75-72, 29 pp.
- Smith, M.W., 1977, Computer simulation of microclimatic and ground thermal regimes: test results and program description, Indian and Northern Affairs, Arctic Land Use Research, 75-76-72, 74 pp.

- Smith, M.W. and A. Tvede, 1976, Computer prediction of frost penetration beneath highways, Report presented to the Ministry of Transport and Communications, Government of Ontario, 39 pp.
- St-Onge, D.A., 1969, Nivation landforms, Geological Survey of Canada, Paper 69-30, 11 pp.
- Tricart, J., 1956, Etude expérimentale du problème de la gélivation, Biuletyn Periglacjalny 4, 285-318.
- Washburn, A.L., 1973, Periglacial Processes and Environments, Edward Arnold (Publ.) Ltd., London, 320 pp.
- White, S.E., 1976, Is frost action really only hydration shattering? A review, Arctic and Alpine Research, Vol. 8, No. 1, 1976, 1-6.
- Wiman, S., 1963, A preliminary study of experimental frost weathering, Geografiska Annaler 45, 113-121.

5.1 ADDITIONAL READING

- Anderson, D.L., 1970, Phase boundary water in frozen soils, U.S. Army Corps of Engineers, CRREL spec. report 154, (13 pp.).
- Anderson, D.M. and A.R. Tice, 1972, Predicting unfrozen water contents in frozen soils from surface area measurements, Highway Research Record, 393, Frost Action in Soils, 12-23.
- Annersten, L., 1966, Interaction between surface cover and permafrost, Biuletyn Periglacjalny 15, 22-33.
- Beck, A.E., F.M. Anglin and J.H. Sass, 1971, Analysis of heat flow data - in situ thermal conductivity measurements, Canadian Journal of Earth Science 8, 1-19.

- Beck, A.E. and J.M. Beck, 1958, On the measurement of thermal conductivities of rocks by observations on a divided bar apparatus, Transactions, American Geophysical Union, 39, 1111-23.
- Beck, A.E. and A.S. Judge, 1969, Analysis of heat flow data - I, Detailed observations in a single bore hole, Royal Astronomical Society Geophysical Journal, 18, 145-158.
- Benedict, J.B., 1970, Frost cracking in the Colorado Front Range, Geografiska Annaler, 52A, 87-93.
- Benedict, J.B., 1970, Downslope soil movement in a Colorado alpine region: rates, processes and climatic significance, Arctic and Alpine Research, 2, 165-226.
- Benninghoff, W.S., 1952, Interaction of vegetation and soil frost phenomenon, Arctic 5, 34-44.
- Birch, F., 1950, Flow of heat in the Front Range Colorado, Geological Society of America, Bulletin 61, 567-630.
- Bostock, H.S., 1961, Physiography and resources of the Yukon, Canadian Geographical Journal, 63, 4, 112-119.
- Brewer, M.C., 1958, Some results of geothermal investigations of permafrost in Northern Alaska, Transactions, American Geophysical Union, 39, 19-26.
- Brown, W.G., 1964, Difficulties associated with predicting depth of freeze or thaw, Canadian Geotechnical Journal 1, 215-226.
- Carson, J.E., 1963, Analysis of soil and air temperatures by fourier techniques, Journal of Geophysical Research, 68, 2217-2232.
- Cook, F.A., 1955, Near surface soil temperature measurements at Resolute Bay, Northwest Territories, Arctic 8(4), 237-249.

- Crawford, C.B. and R.F. Legget, 1957, Ground temperature investigations in Canada, Engineering Journal, Vol. 40, No. 3, 263-269.
- Crawford, C.B. and G.H. Johnston, 1971, Construction on permafrost, Canadian Geotechnical Journal 8, 236-251.
- Davies, J.A. and C.D. Allen, 1973, Equilibrium, potential and evaporation from cropped surfaces in Southern Ontario, Journal of Applied Meteorology, 12, 649-657.
- Dunn, J.R. and P.P. Hudec, 1972, Frost and sorption effects in argillaceous rocks, Highway Research Record 393, Frost Action in Soils, 67-78.
- Dyke, L., 1979, Bedrock heave in the central Canadian Arctic, Geological Survey of Canada Paper 79-1A, 241-246.
- Embleton, C. and C.A.M. King, 1971, Glacial and Periglacial Processes, Macmillan of Canada, Toronto, 608 pp.
- Fahey, B.D., 1979, Frost heaving of soils at two locations in southern Ontario, Canada, Geoderma, 22 (1979), 119-126.
- Fahey, B.D. and R.J. Gowan, 1979, Application of the sonic test of experimental freeze-thaw studies in geomorphic research, Arctic and Alpine Research, Vol. 11, No. 2, 1979, 253-260.
- Fraser, J.K., 1959, Freeze-thaw frequencies and mechanical weathering in Canada, Arctic, 12, 40-53.
- French, H.M., 1970, Soil temperatures in the active layer, Beaufort Plain, Arctic, 23, 229-239.
- French, H.M., 1976, The Periglacial Environment, Longman Pub. Ltd., London and New York, 309 pp.
- Ives, J.D., 1966, Blockfields, associated weathering forms on mountain tops and the nunatak hypothesis, Geografiska Annaler, 48, 220-223.

- Jumikis, A.R., 1966, The frost penetration problem in highway engineering, Rutgers University Press, New Brunswick, New Jersey, 162 pp.
- Kazemi, H. and T.K. Perkins, 1971, A mathematical model of thaw-freeze cycles beneath drilling rigs and production platforms in cold regions, Journal of Petroleum Technology, March: 381-390.
- Low, P.F. and C.W. Lovell, 1959, The factor of moisture in frost action, Highway Research Record, Bull. 225, 23-44.
- McGraw, R., 1972, Frost heaving versus depth to water table, Highway Research Record 393, Frost Action in Soils, 45-55.
- Miller, R.D., 1972, Freezing and heaving of saturated and unsaturated soils, Highway Research Record 393, Frost Action in Soils, 1-11.
- Penner, E., 1959, The mechanisms of frost heaving in soils, Highway Research Bulletin 225, 1-22.
- Penner, E., 1963, Frost heaving in soils, in: Proceedings, 1st International Permafrost Conference, National Academy of Science, National Research Council of Canada, Pub. 1287, 197-202.
- Penner, E., 1970, Thermal conductivity of frozen soils, Canadian Journal of Earth Science, 7, 982-987.
- Penner, E., 1972, Influence of freezing rate on frost heaving, Highway Research Record 393, Frost Action in Soils, 56-62.
- Penner, E., 1973, Frost Heaving Pressures in Particulate Materials, Division of Building Research, Research Paper 579, National Research Council of Canada, 379-385.
- Penner, E., 1974, Frost Heave Uplift Forces on Foundations, Division of Building Research, Research Paper 635, National Research Council of Canada, 10 pp.

- Potts, A.S., 1970, Frost action in rocks - some experimental data, Transactions, Institute of British Geographers, 49, 109-124.
- Sass, J.H., A.H. Lachenbruch and R.J. Munroe, 1971, Thermal conductivity of rocks from measurements on fragments and its application to heat-flow determinations, Journal of Geophysical Research, 76, 3391-3401.
- Taber, S., 1929, Frost heaving, Journal of Geology 37, 428-461.
- Taber, S., 1930, The mechanics of frost heaving, Journal of Geology, 38, 303-331.
- Thompson, R.D. and B.D. Fahey, 1977, Energy balance and ground thermal regime studies, Broughton Island, Northwest Territories, Canada, Arch. Met. Geoph. Biokl. Ser. A, 25, 251-272.
- Thorn, C.E., 1979, Bedrock freeze-thaw weathering regime in an alpine environment, Colorado Front Range, Earth Surface Processes, Vol. 4, 211-228.
- Tourenq, C., 1970, La gélivité des roches (application aux granulats), Rapport de recherche No 6, Ministère de l'équipement et du logement, Laboratoires des ponts et chaussées.
- Williams, P.J., 1968, Properties and behaviour of freezing soils, National Research Council of Canada Research Paper No. 259, 119 pp.
- Williams, G.P. and L.W. Gold, 1976, Ground temperatures, Canadian Building Digest, 180, Division of Building Research, National Research Council, 4 pp.

NOTES DE RECHERCHE / RESEARCH NOTES

- * 1. P.G. Johnson, "The Degradation of the Donjek Glacier Neoglacial Moraine, St-Elias Mts., Yukon Territory, Canada", 9 p., February 1972, \$0.50.
- * 2. C.L. Dudley, "A Note on Reinvestment Assumptions in Choosing Between Net Present Value and Internal Rate of Return", September 1972, \$0.50.
- * 3. L. Ploegaerts, "Étude critique et comparative des plans d'urbanisme et de développement municipaux préparés depuis 1967 sur le territoire de la Communauté Régionale de l'Outaouais", 81 p., mars 1973, \$1.25.
- * 4. J.E. (McCabe) Albert and P. Harrison, "Jurisdictional Problems of New-Brunswick Coastal Zones", 32 p., May 1974, \$1.50.
- * 5. C.L. Dudley, "A Theoretical Financial Analysis of the Long Term Subsidy Value of the Regional Development Incentive Program in Canada: 1969-1972; A Summary", 32 p., October 1974, \$1.50.
- 6a. M. Kugler-Gagnon, "Computer Processing of Geological and Geotechnical Data for Urban and Land-Use Planning", 29 p., March 1975, \$1.50.
- 6b. M. Kugler-Gagnon, "Traitement informatique des données géologiques et géotechniques pour l'aménagement urbain et péri-urbain, 28 p., mars 1975, \$1.50.
- 7. C.L. Dudley, "The Weakness of Financial Location Incentives in Promoting Regional Development", 39 p., April 1975, \$1.50.
- 8. P. Harrison, "Spatial Externalities and the Problem of Resource Control", 15 p., May 1975, \$1.00.
- 9. P.G. Johnson, D. Cossette, D. Conway, C. Lok, "Preliminary Report: Environmental Controls on Geomorphologic Processes, Grizzly Creek, South West Yukon Territory", 108 p., August 1976, \$4.00.
- * 10. L. Ploegaerts, "Étude comparative des plans de zonage sur le territoire de la Communauté Régionale de l'Outaouais", 95 p., mai 1976, \$4.00.
- 11. G.P.F. Steed, "An Historical Geography of the Canadian Clothing Industries: 1800-1930's", 52 p., November 1976, \$2.75.
- 12. R.A. Roberge, "Investment Decisions, Comparative Costs, and the Evolving Location Pattern of the Canadian Pulp and Paper Industry", 38 p., December 1976, \$2.00.
- * Réserve épuisée / Out of stock

13. P.F. Ricci, "Spatial Analysis Through Carrying Capacity", 24 p., January 1977, \$1.75.
14. P. Harrison, "Spatial Demand Under Conditions of Substitution: A Disgrammatic Exposition", 20 p., February 1977, \$1.50.
15. P.F. Ricci, "From Public Announcement to Completed Construction: A Study of the 12 year Impact of a Water Resource Project on Property Values", 23 p., June 1977, \$1.75.
16. P.F. Ricci, and V. Maclaren (ed.), "Selected and Annotated Readings on Planning Theory and Practice", 72 p., September 1977, \$3.00.
17. R. Wesche, "Modern Agricultural Settlement in Rondonia, Brazil", 31 p., August 1977, \$1.50.
18. P. Harrison, "Decision Information and Coastal Management: Some Preliminary Remarks", 15 p., August 1978, \$1.50.
19. A.G. Lewkowicz, "An Approach to the study of Surface Wash: The Case of the Laboratory for Experimental Geomorphology, Leuven, Belgium", 42 p., April 1978, \$2.50.
20. V. Berdoulay, "Notes sur les idéologies comme l'objet d'étude géographique", 23 p., mars 1979, \$1.75.
21. S. Ansari, "Spatial Variations in Levels of Socio-Economic Development of Ontario and the Industrial Structure: an Empirical Test", 66 p., March 1979, \$4.50.
22. D.A. St-Onge, "Forages au roc, Région Nord de Montréal", 113 p., juillet 1979, \$8.00.
23. M. Phipps, "Information Theory and Spatial-Ecological Analysis: The "Pegase" Procedure, 45 p., 2 fig., September 1979, \$3.00.
24. G.P.F. Steed and M. Appana, "Preservation, Rationalization and Orderly Adaptation: Canada's Footwear Sector", 35 p., September 1979, \$2.50.
25. Felix A. Kwamena and Peter Harrison, "Canada's Offshore Resources: Frameworks for Management", 215 p., November 1979, \$12.50.
26. Peter Harrison, "Managing Canada's Ocean Area: Institutions, Client Groups, and Co-ordination", 30 p., December 1979, \$2.00.
27. Felix Kwamena, "Canada's Offshore Resources: The Problem of Integrated Planning in Canada's 200-mile Economic Zone", 27 p., December 1979, \$2.00.
28. Peter Harrison, "Canada: Energy Futures, Energie et l'Avenir", 61 p., April 1980, \$5.00.

29. Michel Phipps, "Recherches écologiques pour l'aménagement forestier: Les Cédraies du Moyen Atlas du Sud-Ouest".
 - a) Le contexte, 38 p., juin 1980, \$2.50.
 - b) L'approche méthodologique et l'espace écologique, 75 p., janvier 1981, \$5.50.
 - c) Les types de communautés végétales, 122 p., mars 1981, \$5.50.
30. Guy Steed, "National Circumstances, Expectations Conflict and Compromise: Canada's Textile and Clothing Policy", March 1981, \$2.50.
31. Peter Harrison, Charles Brassard, Donald Wright, "Capital Expenditures to Develop the Hibernia Field: Sectoral and Spatial Distributions of Impacts", June 1981, \$3.00.
32. Edmond Kayser, "Les routes et le développement des transports au XIXe siècle: la formation des réseaux luxembourgeois", 32 p., août 1981, \$2..50.
33. Don Tate, "The Analysis of Manufacturing Employment in Canada Using Shift-Share Analysis: An Examination of Methodology and an Empirical Test", 66 p., December 1982, \$6.00.
34. Véronique Dewez et Daniel Lagarec, "La dualité glaciaire - périglaciaire et l'origine de certaines formes dues à la fonte de glace", 77 p., juin 1982, \$7.00.
35. Ghyslain Poulin et Michel Phipps, "Ambiance et structure forestières: Une méthode d'approche pour l'étude du loisir en forêt", 33 p., août 1982, \$2.50.
36. Marie-Anne Geurts, "Observations géomorphologiques dans la région de Huamachuco, Andes centrales péruviennes", 27 p., octobre 1982, \$2.50.
37. R. Needham, "The Cosmopolite - Localite Model: Newspaper Types and Natural Hazard Information Potentials", 42 p., November 1982, \$3.50.
38. P. Vasconcelos, "Le secteur informel urbain", 81 p., septembre 1982, \$7.00.
39. M.-A. Geurts, D. Lagarec, F. Sarrazin et S. Lemaître, "Pluie Pollinique de l'été 1982 dans la vallée du Gladstone Creek (Yukon), 39 p., Mai 1983, \$4.00.
40. M. Phipps, "Étude d'un processus de recolonisation par le cèdre (Cedrus Atlantica Man.) Analyses de configuration du peuplement", 66 p., Mai 1983, \$6.00.

41. R. Roberge, "A Spatial Information System for Predicting Hazard at Railway Crossings", 24 p., October 1983, \$3.50.
42. A. Gilbert, "Les abandons de ferme et la concentration de l'habitat dans l'Outaouais rural québécois", Ingo Eberle (Mayenne), traduit par Anne Gilbert (Ottawa), 36 p., novembre 1983, \$4.00.
43. P. Johnson, "Glaciological Conditions and Geomorphological Interpretation", 20 p., November 1983, \$3.00.
44. P. Johnson, "Holocene Glaciological Conditions, Southwest Yukon", 19 p., November 1983, \$3.00.
45. E. Kayser and F. Kwamena, "The Atlantic Fisheries and Community Development: A Conceptual Framework", 23 p., July 1984, \$3.50.
46. D. Lagarec et M.-A. Geurts, "Les caractéristiques climatiques de la pluie pollinique dans la vallée du Gladstone Creek, Chaîne Ruby, Territoire du Yukon", 33 p., décembre 1984, \$4.00.
47. V. Dewez, D. Lagarec, M. Phipps, "The Distribution of some Periglacial Landforms in Northern Quebec (Canada) as related to Climate: An Information System Approach", 53 p., décembre 1984, \$5.00.
48. Roger A. Roberge, "The Level of Urban Services in Canadian Resource Towns: A Comparative Analysis", 26 p., June 1985, \$3.50.
49. Johanne Frégeau, "L'évolution du théâtre franco-ontarien: éléments d'un nouvel espace culturel", 41 p., août 1985, \$4.00.
50. Wayne H. Pollard, "A Numerical Simulation of Bedrock Thermal Regimes in the Discontinuous Permafrost Zone", 45 p., September 1985, \$4.50.